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ABSTRACT

Xenoliths that were originally granite and gneiss occur in diabase in the Tortilla Mountains 70 miles north of Tucson, Arizona. Relict quartz and newly formed granophyric intergrowths, perthites, and high- and low-temperature feldspars are distinctive features of certain of the xenoliths. These features are attributed to local production of granitic magma by partial fusion of the xenoliths. Transfer of material between the newly formed magma and the diabase is also shown.

High- and low-temperature feldspars, distinguished by habit and optical properties, exist together. Both high and low plagioclases occur in the same thin section and are associated, respectively, with high and low types of potassium feldspar. The more albitic high-temperature plagioclase is An_{20}, 2V 65°–75° negative; the low-temperature feldspar is An_3, 2V 84° positive. The potassium feldspars consist of microcline corresponding to the low form and a cryptoperthitic potassium feldspar of Or_{65} composition lying in part between the sanidine-anorthoclase and orthoclase curves on the 2V-composition diagram of Tuttle.

The high-temperature plagioclases have the lathlike shape, euhedral form, and strong zoning typical of feldspars of volcanic rocks; the low-temperature feldspars are granular or "patch-perthites" and resemble feldspars of plutonic rocks. The "volcanic" types, including cryptoperthites, are attributed to crystallization from the newly formed melt; the "plutonic" types, including "patch-perthites," to recrystallization of some of the newly formed "volcanic" material.

GENERAL NATURE OF THE XENOLITHS

Geologic Setting

Large xenoliths, originally granite and granitic gneiss but now strongly modified, occur in diabase in the Tortilla Mountains of central Arizona, about 70 miles north of Tucson (White, 1955). Their location is 6,700 feet S 29°E from the post office at the small settlement of Kelvin, Pinal County, in the SW part of Sec. 7, T. 4 S, R. 14 E. Near by are other xenoliths that are unchanged from the parent granite and gneiss.

The geologic setting is shown in figure 1. Dikelike bodies of diabase up to 1,000 feet wide intruded the granite and gneiss, the parent rocks of the xenoliths. The diabase, which is part of the central Arizona diabase of probable Cretaceous age, is mainly quartz diabase in the local area. However, near the modified xenoliths the mineral composition is that of hornblende-quartz diorite. The granite, which is coarse grained, porphyritic, and similar to the Precambrian granite of the region, consists of large grains of microperthite (as much as 5 cm. long) set in a coarse matrix of albitic plagioclase (An_{5-15}), quartz, microcline (2V 84° negative, grid twinning), and minor biotite. The gneiss, which is closely associated and mixed with the granite, is composed of quartz, albite (An_5, 2V 79° positive), microcline (2V 80° negative, grid twinning), and minor biotite and muscovite.

Three xenoliths displaying marked changes were selected for study and are denoted xenolith 1, xenolith 2, and xenolith 3 (fig. 1). Xenolith 1 is an irregular dike-shaped body about 50 feet long by 5–10 feet wide. Xenolith 2, which is 600 feet

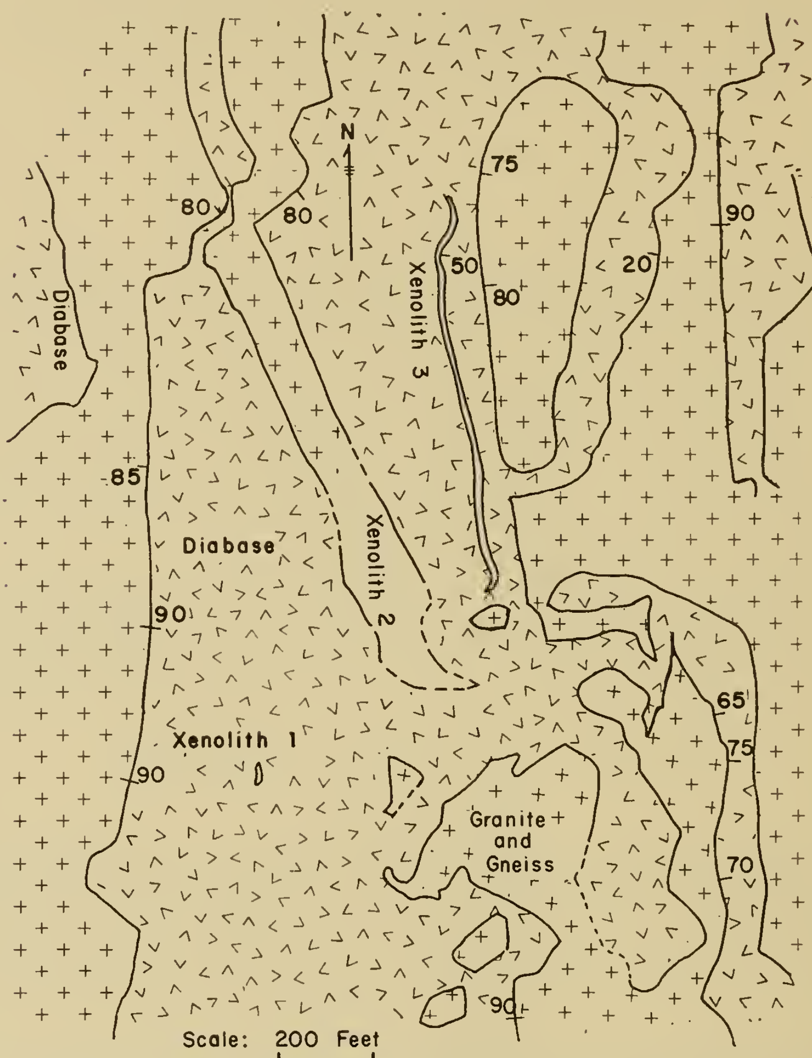

Fig. 1. Geologic setting of Tortilla range xenoliths. Xenolith 1, xenolith 2, and xenolith 3 are strongly modified; other xenoliths are unchanged.

long by 200 feet wide, is not completely surrounded by diabase, but is a tongue of modified granitic material. Xenolith 3 is distinctly dike-like, 900 feet long and 5–20 feet wide.

Petrography

Each xenolith consists of a central zone of granitic granophyre and a marginal zone, about 5 feet wide, of hornblende granophyre that has the composition of hornblende-quartz diorite. The central zone (apart from compound quartz grains, which are relics from the original parent rocks) consists of about 32 per cent quartz; 50 per cent albite and potassium feldspar; 15 per cent oligoclase; and 3 per cent

biotite, magnetite, and chlorite, together with minor amounts of muscovite, apatite, and sphene. The marginal zone of hornblende granophyre is similar, but is characterized by more abundant and more calcic plagioclase and the presence of hornblende (10–20 per cent).

The modified xenoliths (see pl. 16) consist of relatively large, rounded grains of quartz and feldspar, fine granophyric intergrowths, and a variety of feldspars of both low- and high-temperature types. The large quartz bodies, which are relict quartz inherited from the parent granite and gneiss, have the same coarse size, aggregate structure, and distinctive needlelike inclusions present in the quartz of the parent rocks. However, the outlines of the relict quartz are rounded, often embayed, and appear corroded. In the marginal zone, hornblende, biotite, and magnetite form rims around the quartz bodies. Similar relict quartz with corroded outlines and rims has been reported for other siliceous xenoliths in basic rocks (Larsen and Switzer, 1939; Wilson, 1952). A strong lineation produced by parallel alignment of elongated quartz bodies is present in the gneiss but not in the xenoliths.

Notably different from the relict quartz is a later quartz composed of comparatively minute single crystals free from the needlelike inclusions and usually subhedral to euhedral. Most of this younger or newly crystallized quartz occurs in individual grains forming part of a fine-grained granophyre or microgranite. Variation in grain size is extreme, ranging from less than 0.001 mm. to 1 mm. or more. Many of the crystals have the strong development of pyramid faces often found in the quartz of volcanic rocks.

The granophyric intergrowths are dominantly potassic feldspar-quartz, but occasionally a minor amount of albite-quartz is present. The intergrowths, which are rodlike, cuneiform, and feathery types, are crudely spherical around a central plagioclase. The granophyre appears to be similar to many granophyres mentioned in the literature (Hawkes, 1929; Mountain, 1936).

In the central zone, biotite is the most common ferromagnesian mineral. Chlorite and magnetite also are present, but hornblende is absent. In the marginal zone, hornblende generally predominates; biotite, chlorite, and magnetite usually are present but in subordinate amounts. The hornblende is common igneous hornblende: X pale brown, Y olive-green, Z green changing to blue-green on margins; {010} and {110} common; Z to C about 25°; crystals stumpy to moderately elongated. Two biotites occur: ordinary brown biotite and yellow to orange-brown biotite, 2V 5°–20°. Chlorite, which apparently replaces both hornblende and biotite, is pale green with a radiating fibrous appearance. Muscovite, sphene, and apatite (both needlelike and stumpy) are present throughout the inclusions. Prehnite, clinozoisite, epidote, and calcite are present in the marginal zone in minor amounts.

Several kinds of feldspar of both low- and high-temperature type occur together and can be recognized on the basis of textural and optical properties. These feldspars are:

Granular albite and perthite	Low-temperature form
Core plagioclase	High-temperature and transitional forms
Core albite	Low-temperature form

Mottled plagioclase............................High-temperature and transitional forms
Microcline ....Low-temperature form
Orthoclase cryptoperthite......................High-temperature and transitional forms

The feldspars are treated in detail in the following sections.

FELDSPARS

Optic Measurements

The optic directions X, Y, and Z are located by extinction methods with the three-axis universal stage and are measured with reference to crystallographic directions as given by cleavage, lamellae, and twin axes (Turner, 1947). The measurements are plotted on stereograms containing curves (data from Van der Kaaden, 1951) for low- and high-temperature feldspars. 2V is obtained by the method given by Fairbairn and Podolsky (1951), and in general is reproducible to ± 1°.

Granular Albite and Perthite Albite

In the marginal and central zones, low albite occurs as separate grains (granular albite) and as irregular patches in potassium feldspar (perthite albite). Both types, which are associated with potassium feldspar and quartz, tend to occur in micrograniticaggregates on the margins of crudely spherulitic, granophyric intergrowths.

Optic data are summarized in table 1 and plotted in figures 2 and 3 (crosses). Both measurements of crystallographic directions with respect to the optic directions X, Y, and Z and 2V values consistently indicate low-temperature albite. The composition shown by 29 universal-stage measurements is An_{2-3}. Refractive indices (α 1.529, β 1.533) indicate An_3 (Smith, 1958). Albite twinning is almost universal; pericline twinning was observed in 40 per cent of the grains measured.

TABLE 1

Comparison of Granular Albite and Perthite Albite

Granular albite	Perthite albite
FEATURES OF HABIT AND OCCURRENCE	
Equant, subhedral, cloudy grains; outside edge of granophyric intergrowths	Irregular cloudy patches in potassium feldspar (patch-perthite); outer parts of granophyric intergrowths
Albite and pericline twins	Albite and pericline twins
OPTICAL MEASUREMENTS	
2V 83° positive	2V 82° positive
⊥ {010} 89° 74° 16°	
⊥ {001} 70° 24° 78°	⊥ {001} 70° 23° 78°
⊥ rhombic section 76° 18° 77°	
[010] 89° 76° 14°	
α 1.529, β 1.533	

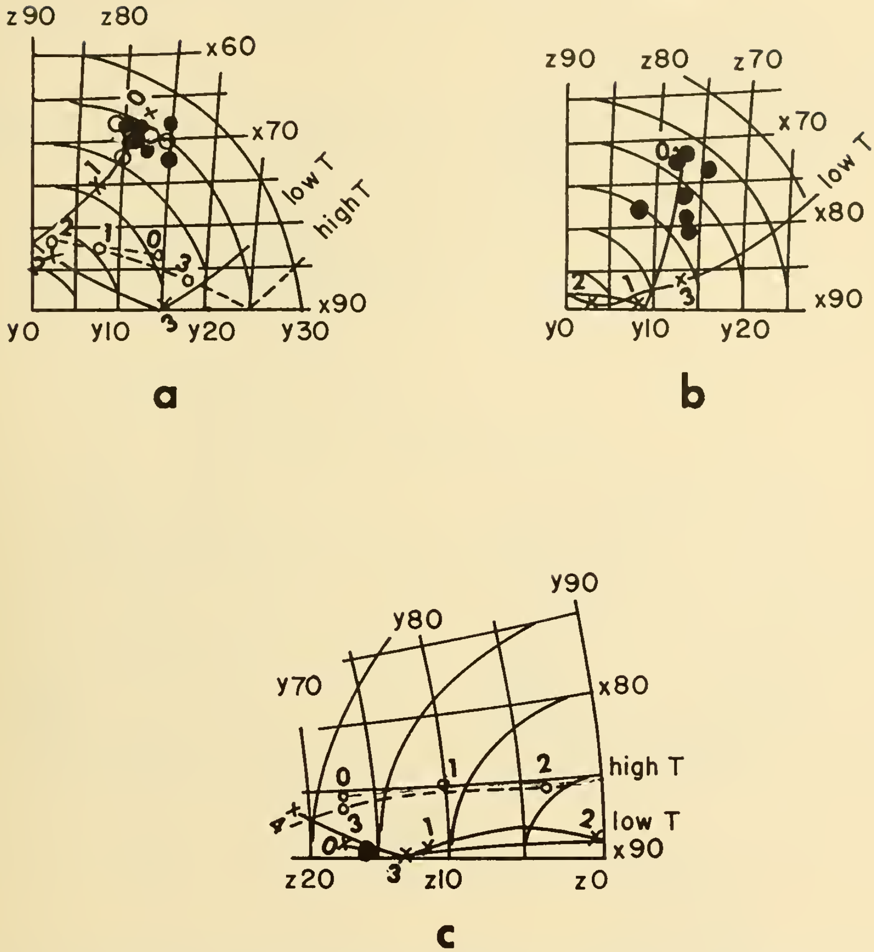

Fig. 2. Crystallographic directions in relation to optic directions in granular albites and perthite albites. Composition curve for low-temperature form shown as full line; composition curve for high-temperature form shown as dashed line. On curves, numbers 1, 2, 3 stand for 10, 20, and 30 per cent An. *a*, Granular albites (solid circles) and perthite albites (open circles), ⊥ {001}; *b*, granular albites, ⊥ rhombic section; *c*, granular albites, ⊥ {010}, average of 12 measurements.

Core Plagioclase

A type of feldspar different from the low-temperature albite is found in the central portions of granophyric intergrowths and is termed core plagioclase (pl. 17). The core plagioclases are clear, commonly euhedral, and lathlike; they are easily differentiated from the cloudy, equant albites on the outer parts of the intergrowths.

Universal-stage measurements of the core plagioclases of the central zone (see fig. 4, *a*, *b*, *c*) indicate a composition of about An_{20} with a range from An_{18} to An_{22}. The composition from refractive indices (α 1.539, β 1.543, γ 1.546) is An_{21} from curves by Smith (1958). In the marginal zone of the xenoliths the composition

(fig. 4, *d, e*) ranges from An_{53} in the central parts of the crystals to about An_{18} on the margins. The central parts of these feldspars are frequently altered to epidote and clinozoisite.

The 2V values (figs. 3, 5) indicate high-temperature forms and gradational transformations toward the low form. This is suggested also by the measurements

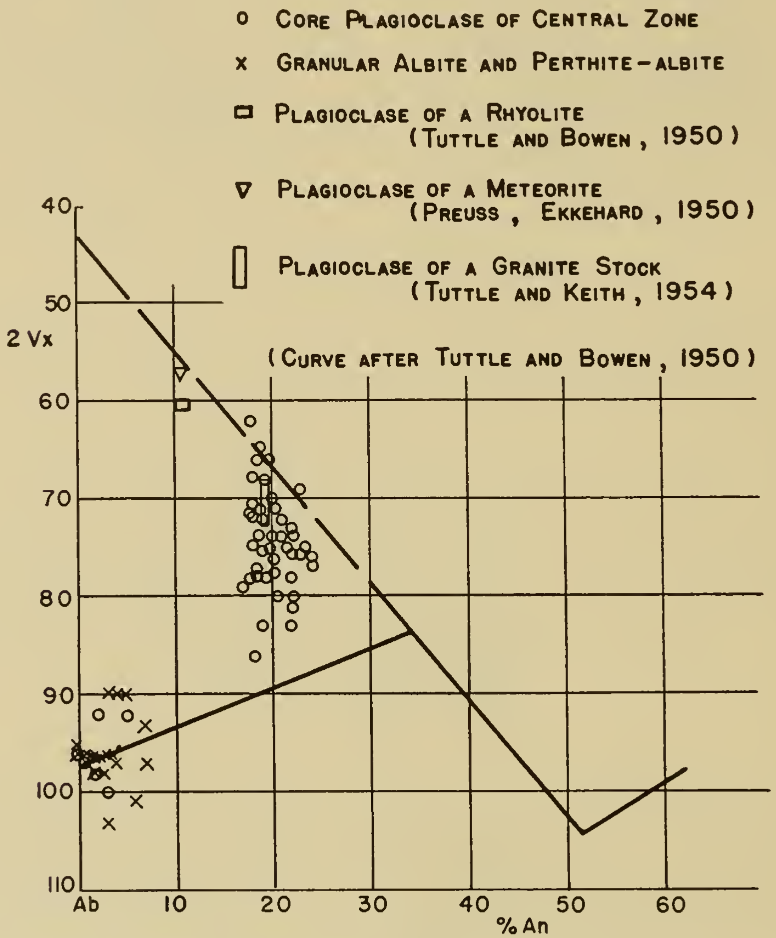

Fig. 3. 2V-composition diagram of granular and perthite albites (crosses) and core plagioclases (circles) of central zone. Dashed curve for high-temperature forms.

of crystallographic directions in relation to the optical directions. The presence of high-temperature and transitional forms is compatible with the findings of Smith and Yoder (1956) and others, in which volcanic-type plagioclases are found to be in various states of inversion and not to constitute a unique high-temperature series. The strong zoning, lathlike habit, euhedral crystals, rims of potassium feldspar, and genetic connection with diabase are features of volcanic-type feldspars.

Locally in the central zone of xenolith 2, the core feldspars have a composition of An_3 and have the low-temperature form as shown both by 2V values (fig. 3)

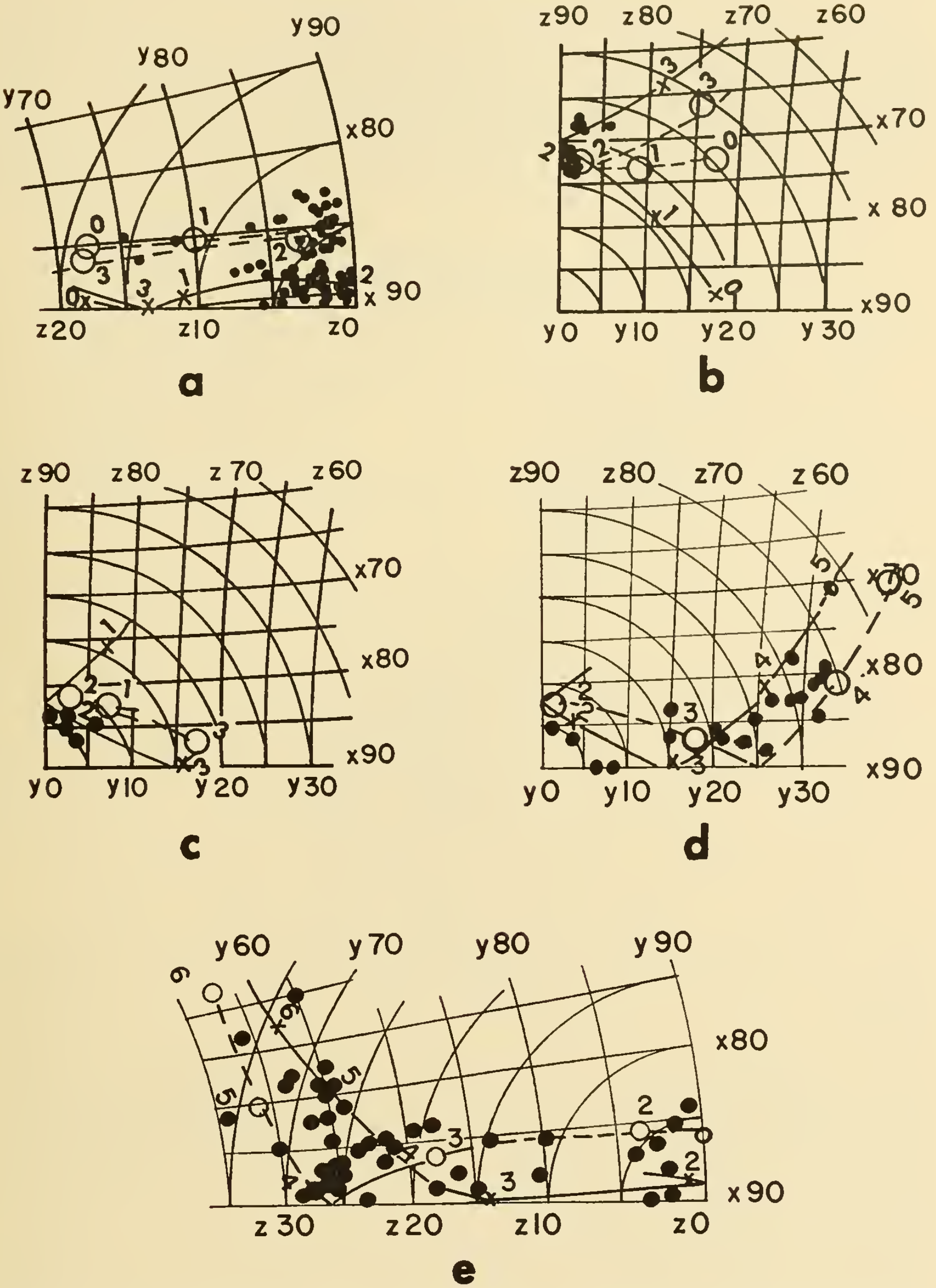

Fig. 4. Crystallographic directions in relation to optic directions in core plagioclases: *a, b, c,* central zone; *d, e,* marginal zone. Spread of values in marginal zone is due chiefly to strong zoning of feldspars. Dashed curve for high-temperature forms. *a,* ⊥ {010}; *b;* [001]; *c,* ⊥ {001}; *d,* ⊥ {001}; *e,* ⊥ {010}.

and by measurements of crystallographic directions with reference to optic directions (fig. 6). In habit and occurrence these "core albites" are the same as the high-temperature core plagioclase. It is assumed that such core albites represent forms fully transformed from the original high-temperature structure.

Many of the core plagioclases, particularly in the central zone, appear to be untwinned. However, under high magnification and resolution, faint closely spaced

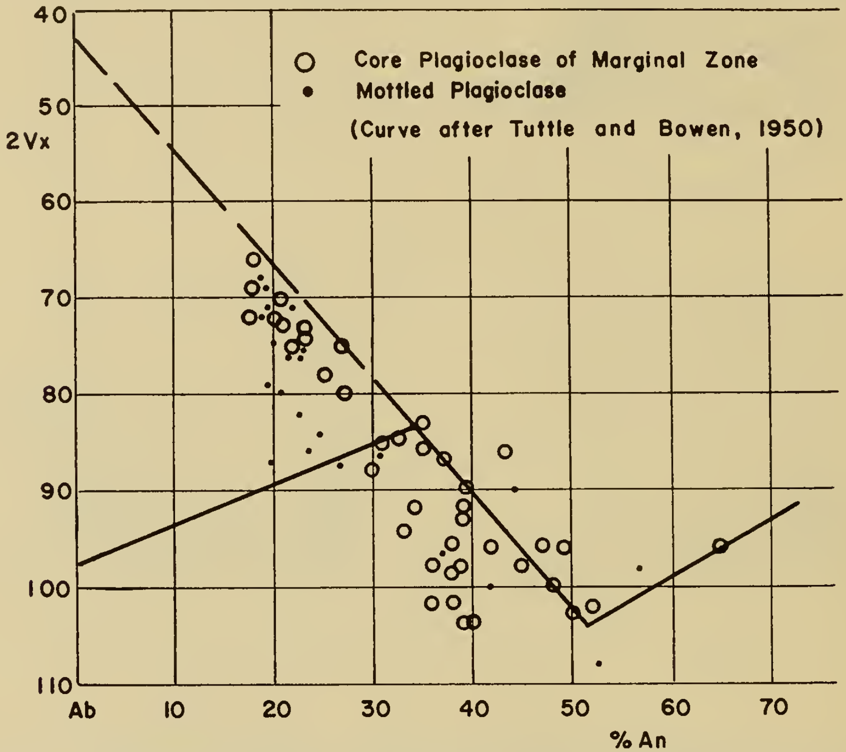

Fig. 5. 2V-composition diagram. Core plagioclases (circles) from marginal zone; mottled plagioclases (solid circles) from both central and marginal zones. Dashed curve for high-temperature forms.

lamellae parallel to {010} are seen. Various degrees of development of albite twinning occur. This seems to be similar to a report by Oftedahl (1948), who describes albite twinning grading into submicroscopic twinning. Carlsbad, carlsbad-albite, manebach-ala, and pericline twins are present. The carlsbad twins are often accompanied by rims of potassium feldspar in lattice continuity with each individual. This suggests that they are growth twins.

Elongated tabular plagioclases that are probably similar to the core plagioclases have been observed in many granophyres or micropegmatites (Wager, Weedon, and Vincent, 1953; Wilson, 1952; Strauss, 1947).

Mottled Plagioclase

A feldspar designated "mottled plagioclase" to distinguish it from the associated feldspars is characterized by large size (averaging 1 cm. but ranging up to 5 cm.),

corroded outlines (large feldspars, pl. 16), the presence of finely intergrown quartz, and an irregular "patchy" and speckled appearance (pls. 18, 19).

Optical data are plotted in figures 5 and 7. The composition of the mottled plagioclase of the central zone (fig. 7) ranges from about An_{24} to An_{20} because of slight zoning in the grains. Mottled plagioclases in the marginal zone, which are

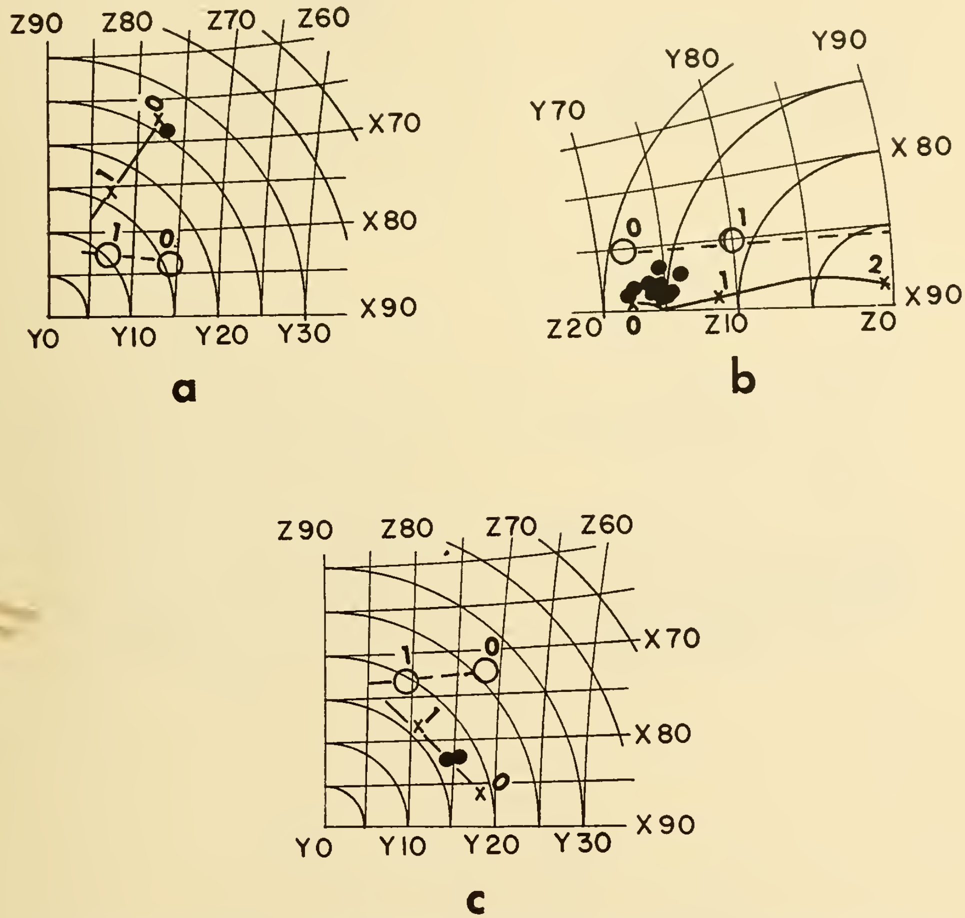

Fig. 6. Crystallographic directions in relation to optic directions in low-temperature core plagioclases. Dashed curve for high-temperature feldspars. *a*, ⊥ {001}; *b*, ⊥ {010}; *c*, [001].

strongly zoned, range in composition from An_{58} to An_{20} (fig. 7). Determinations of composition from refractive indices give values within a few per cent of those found from orientation of the optic indicatrix. Values of 2V (fig. 5) correspond closely with those of the core plagioclases. The distribution of 2V values indicates that the mottled plagioclases also range from high-temperature through intermediate to low-temperature forms.

The mottled plagioclase and core plagioclase differ so markedly in size and texture that it is unlikely that both could crystallize simultaneously from a common medium. The large size and the nature of the mottled plagioclase aggregates sug-

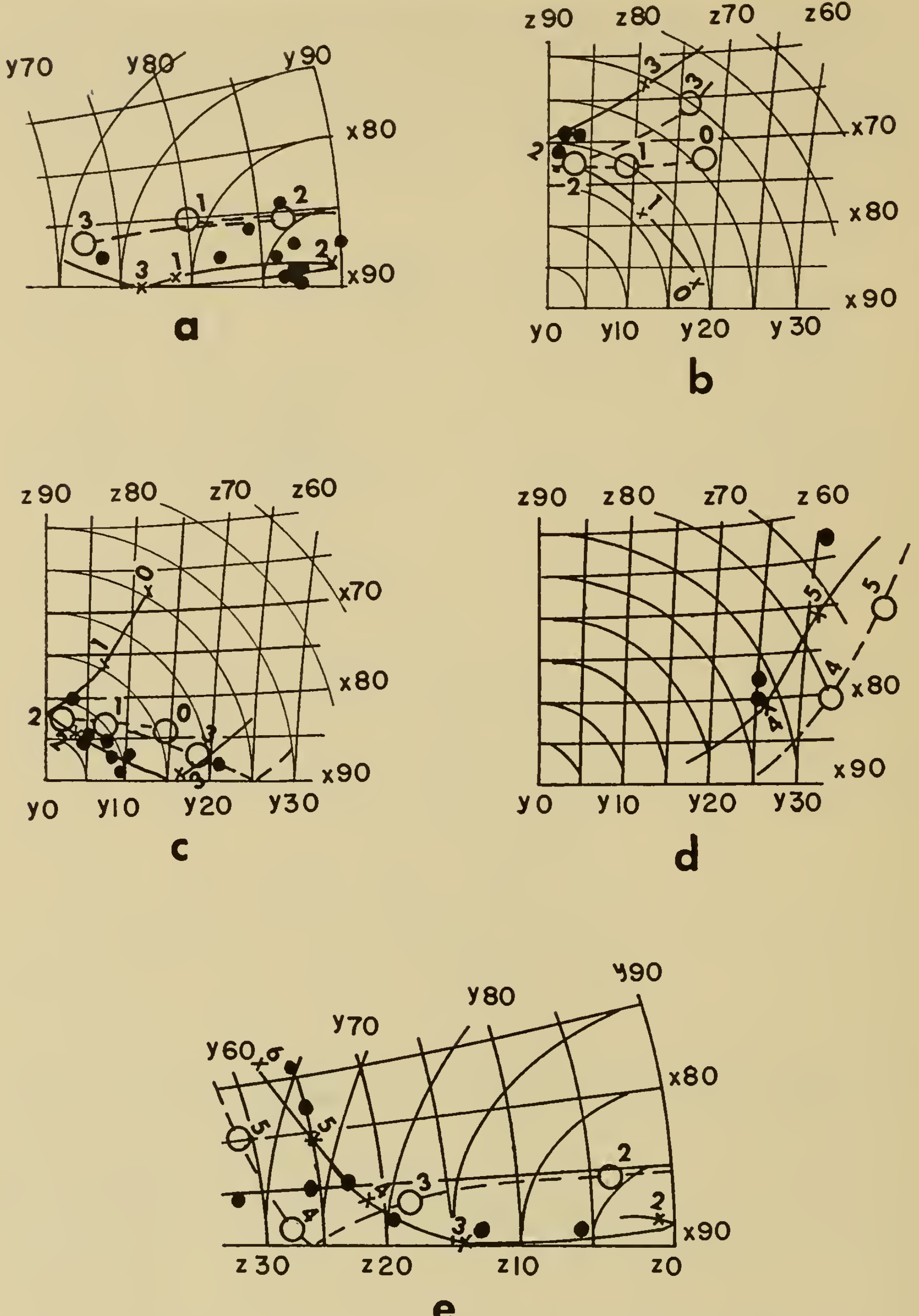

Fig. 7. Crystallographic directions in relation to optic directions in mottled plagioclases: *a*, *b*, *c*, central zone; *d*, *e*, marginal zone. Dashed curve for high-temperature feldspars. *a*, ⊥ {010}; *b*, [001]; *c*, ⊥ {001}; *d*, ⊥ {001}; *e*, ⊥ {010}.

gest that they are modified relics inherited from the parent granite and gneiss. If this is so, they have changed in composition and in internal texture, for similar plagioclases are not found in the unaltered granite and gneiss. Modification has resulted in corrosion, development of the patchy texture, and change in composition from alkali feldspar to oligoclase (andesine to labradorite in the marginal zone).

TABLE 2

Comparison of the Two Groups of Potassium Feldspars

Orthoclase cryptoperthite	Microcline
FEATURES OF HABIT AND OCCURRENCE	
Clear, untwinned, often euhedral; {001} and {010} common	Murky, some manebach twins, subhedral to anhedral; {001} and {110} common
Associated core plagioclase in lattice continuity	Associated low albite
Granophyric intergrowths, rims, antiperthite	Granular aggregate or patch-perthite
Cryptoperthite, microscopic to submicroscopic albite blebs and lamellae along rhombic section	Relatively coarse patch-perthite
OPTICAL MEASUREMENTS	
2V 49°–77°, av. 68°	2V 80°–86°, av. 82°
⊥ {001} 83° 8° 86° ⊥ {010} 85° 88° 5°	⊥ {001} 79° 11° 86° {010} not developed
α 1.522, γ 1.528	α 1.519, γ 1.525

Orthoclase Cryptoperthite and Microcline

Differences in habit and optical properties indicate two groups of potassium feldspars classed, respectively, as orthoclase cryptoperthite and microcline. Location is distinctive for each group. Typically, cores of high-temperature plagioclase are surrounded by fine granophyric intergrowth containing orthoclase cryptoperthite. Fine intergrowth becomes coarser away from the core, and with increasing coarseness patch-perthite with microcline and low albite frequently takes the place of the cryptoperthite. Farther out, separate grains of microcline, low albite, and quartz form a relatively coarse granular aggregate. A summary of the two groups of feldspars is given in table 2. Optical data are plotted in figures 8 and 9.

If the composition is only approximately known, the 2V can be used to classify the potassium feldspars (Tuttle, 1952). Refractive indices of the microclines (α 1.519, γ 1.525) indicate a composition of about Or_{90} from curves by Tuttle. Refractive indices of the cryptoperthites are higher and somewhat variable, ranging from α 1.521 and γ 1.526 to α 1.522 and γ 1.528. This indicates a composition from

about Or_{75} to Or_{60} for the cryptoperthites. Hewlett (1959) has emphasized the uncertainties in determining composition from refractive indices. However, the composition as determined from refractive indices appears to be sufficiently accurate for classification purposes. The 2V-composition fields of the two groups of feldspars are shown in figure 9.

The "orthoclase cryptoperthites" (fig. 9) extend from between the sanidine-anorthoclase and orthoclase curves to the microcline curve. This implies gradations from sanidine to microcline. Similar transitions from the sanidine-anorthoclase

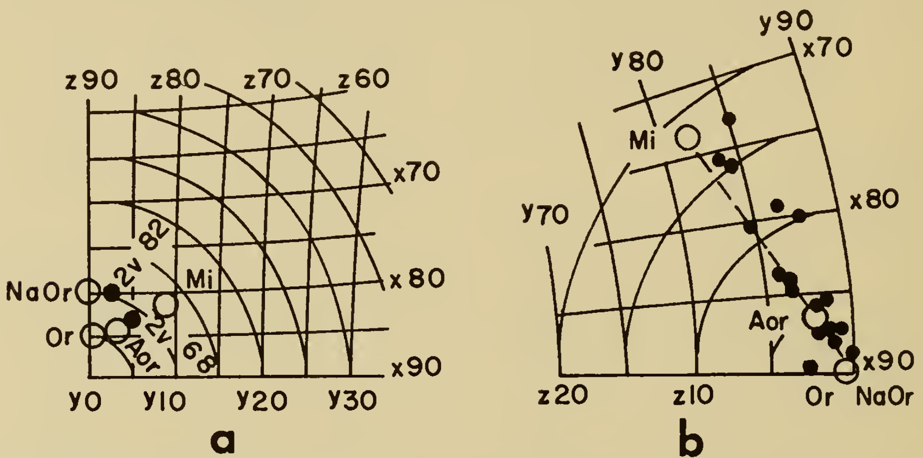

Fig. 8. Crystallographic directions in relation to optic directions in potassium feldspars. Curves and notation after Nikitin (1936), Tröger (1952), and Osten (1953). *a*, Averages of 25 measurements, ⊥ {001} and 2V, microclines (2V 82°) and orthoclase cryptoperthites (2V 68°); *b*, orthoclase cryptoperthites, ⊥ {010}.

series to orthoclase cryptoperthite were shown by Tuttle and Keith (1954). On the basis of the measurements of orientation of the optic directions and 2V, the cryptoperthites would be similarly classified and placed in a sanidine-anorthoclase series with gradations toward microcline (Osten, 1953). The habit and the mode of occurrence of these minerals support the classification based on optical data. Association with high-temperature plagioclase (antiperthite, rims, adjacent granophyric intergrowth), lack of twinning, and clarity of the grains (Folk, 1955) suggest volcanic-type feldspar. Many of the crystals are euhedral, with a predominance of {001} and {010} faces, and are elongated along "a." These are characteristics of high-temperature formation, according to Köhler (1948, 1949). The type of perthite also corresponds to that found in volcanic rocks. The "orthoclase cryptoperthites" range from optically homogeneous to grains in which clear, optically untwinned albite occurs as very thin interlaminations or as spindles along the rhombic section. Intergrowths of this type have been investigated by Chao and Taylor (1940), Köhler (1948), and Ito and Sadanaga (1952).

The "microclines" fall in the region of the microcline-microperthite curve (fig. 9) and are normal microclines in this respect. However, they are not strongly triclinic. The variability of typical microclines from nearly monoclinic to strongly

triclinic is well known. Laves (1952) suggested that there is a continuous gradation from a monoclinic to a triclinic lattice. The optic symmetry of the microclines in this study is similar to that of microcline perthites reported by Wilson (1950). The habits and the occurrence of the microclines support their classification based on optical properties. Association with low-temperature albite, granular texture, and patch-perthite are characteristic of potassium feldspars of plutonic rocks.

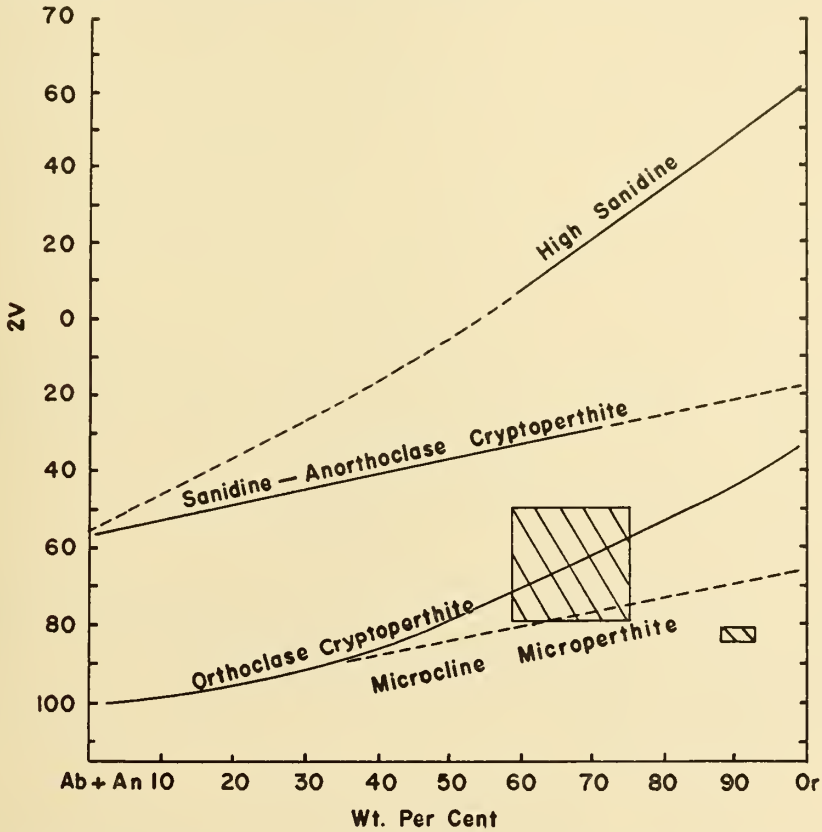

Fig. 9. Large crosshatched square indicates 2V-composition field of orthoclase cryptoperthites; small crosshatched rectangle indicates field of microclines. Diagram after Tuttle (1952) and Tuttle and Keith (1954).

Presence of equant grains, absence of carlsbad twins, presence of manebach twins, and the absence or limited development of {010} crystal faces also suggest a plutonic environment (Köhler, 1948, 1949).

The possibility that the microclines are relics from the original gneiss and granite can be ruled out. The potassium feldspars of the granite display grid twinning and are up to 5 cm. long, compared to 0.6 mm. for the largest potassium feldspars in the xenoliths.

PETROGENESIS

The minerals and textures indicate almost complete transformation of the original granite and granitic gneiss into material with newly created volcanic and plutonic

affinities. The unusual association of low- and high-temperature feldspars is attributed to crystallization of the latter from a newly formed melt, and to solid-state changes involving exsolution, polymorphic transformations, and recrystallization. Transfer of material is shown between xenoliths and diabase. Locally, filterpressing may have occurred.

The granophyric material of the xenoliths is similar to that described in many other studies. Leighton (1954), in a study of the gabbro-granophyre association in Wisconsin, describes a zone of intermediate rocks; cores of plagioclase rimmed by micropegmatite; zoned, green hornblende; a pseudo-diabasic texture; and several other features resembling those of the Tortilla range xenoliths. Emulus and Smith (1959) describe similar feldspar characteristics and similar granophyric material from the Slieve Gullion area, Ireland. Reynolds (1936), Hotz (1953), Jones (1930), Strauss (1947), Mountain (1944), and Hamilton (1956, 1959) mention features resembling those of the xenoliths. The association diabase-granophyre is world-wide and shows similar characteristics in all occurrences.

Partial Melting

Many instances of probable partial melting of granitic rock by basic magma have been recorded (Knopf, 1938; Larsen and Switzer, 1939; Hawkes, 1929; Mountain, 1936; Walker and Poldervaart, 1949; Wager, Weedon, and Vincent, 1953). Characteristic features of the partially fused material are:

1. A matrix of siliceous glass or of granophyric quartz-feldspar intergrowths.
2. Relict grains of quartz with smooth and embayed outlines.
3. Rims of ferromagnesian minerals around relict quartz grains.

Criteria suggesting partial fusion in the Tortilla range xenoliths are as follows:

1. The occurrence of the same textural features noted above, except for the presence of glass.
2. High-temperature form and volcanic affinities of some feldspars.
3. Relative movement of the relict quartz bodies shown by destruction of the original parallel alignment present in the gneiss.
4. The evidence of filterpressing (discussed in a later section).

The product of partial fusion determined from laboratory experiments (Schairer and Bowen, 1935) is a mixture of quartz-albite-orthoclase approximating to the middle of Bowen's low-temperature trough. This product will be only slightly modified if a small amount of calcium, such as occurs in granitic rocks, is present. As part of the melting process, reaction between liquid and grains of quartz and feldspar (represented in the xenoliths by the relict quartz and mottled plagioclase) would necessarily take place. Reactive solution (term from Bowen, 1922) would explain the corroded margins. The change of composition of relict feldspars necessary to produce the mottled plagioclase is also compatible with what would be expected in the melting process: separate feldspar crystals from the parent rocks would tend to become more calcic in composition by reaction with the melt in accordance with Bowen's reaction relation. A granitic melt (central zone) containing only a small percentage of anorthite would be in equilibrium with plagioclase crystals of about An_{20}. During melting, calcium and aluminum from the melt would tend to be added to the feldspar xenocryst in exchange for sodium, potas-

sium, and silicon. The excess silica could produce the quartz intergrowth in the mottled plagioclase.

The core plagioclases and orthoclase cryptoperthites (later modified by solid-state changes) crystallized from the melt produced by partial fusion. As shown by the feldspar compositions, the melt was granitic in the central zone and much more calcic in the marginal zone. Crystallization of the core plagioclases was followed by growth of potassic feldspars as rims and in granophyric intergrowths. The granophyric intergrowths are ascribed to direct crystallization from the melt. The intergrowths, which consist of volcanic-type quartz and feldspar, are in knife-sharp contact with relict quartz. These features would be difficult to explain by any solid-state recrystallization or replacement process, and are the same as those described for glass and relict quartz.

Although partial melting of inclusions in diabase has been commonly reported, most inclusions are unchanged. For example, numerous granitic inclusions occur in the diabase of the general area, but only three were found which were affected by the diabase. This variability in behavior of diabasic magma toward country rock has been noted by others (Walker and Poldervaart, 1949; Poldervaart, 1952). The diabase magma was only locally active, and some factor other than pure thermal effects must be involved. The factor is believed to be the local introduction of water into the xenoliths, which would sufficiently lower the melting temperature. The idea of the necessity of water is not new. Bowen (1922) states: "Direct melting rather than reactive melting of granitic inclusions to masses of liquid by basaltic magma is not ordinarily to be expected, because the solid granite does not retain the volatile components that aid in lowering the melting temperature of granitic magma below that of basaltic magma." Recent experiments (Tuttle and Bowen, 1953) on natural granites confirm the necessity of adding volatile components in order to lower the melting temperature sufficiently. Analyses of glasses formed by vitrification of xenoliths show high water content (Frankel, 1950; Larsen and Switzer, 1939). In conclusion, the two necessary requirements for the melting are addition of water and heating above minimum temperature.

Solid-State Changes

Stages of unmixing range from optically homogeneous feldspars, to cryptoperthite, to fine microperthite, to patch-perthite, to relatively coarse granular albite and potassium feldspar. The presence of exsolved and optically homogeneous material side by side, with relatively coarse microperthite and separated granular material close by, cannot be attributed to differences in cooling history, intensity of metamorphism, or deformation. Unmixing is spatially controlled, being related to distance from the plagioclase core in the granophyric intergrowths. This suggests that differences in composition of the alkali feldspars may influence ease of formation of perthite and granular material. Tuttle and England (1953) suggest that the unmixing in feldspars is controlled in part by the amount of water vapor. When the amount of water is in excess (denoted by a mica), the feldspar unmixes completely into two feldspars. When the amount of water is small (denoted by hornblende), unmixing is incomplete and perthite results. However, no correlation was noted between unmixing and presence of hornblende or biotite. The unmixing does

correlate, however, with coarseness of texture and distance from the plagioclase cores. This might be related both to concentration of water in the crystallizing system and to composition of the feldspars.

The tendency toward development of transitional states and low-temperature forms from the high-temperature feldspars is attributed to structural transformation. Such "partial inversions" are common in the feldspars of volcanic rocks. The

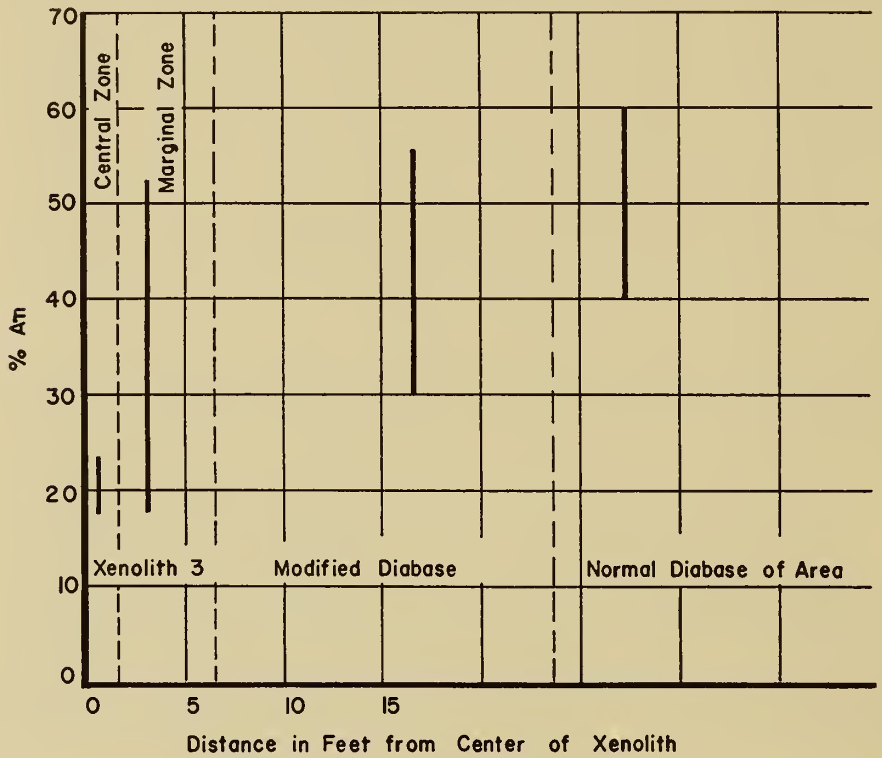

Fig. 10. Composition of plagioclases in xenolith 3 and surrounding diabase. Range of composition (shown by vertical bars) is due chiefly to zoning of feldspars.

unusual core albite (low-temperature), which apparently is a paramorph after the high-temperature form, suggests that inversion is more rapid (i.e., more complete) in the low-calcium feldspars. Although structural transformation toward the low form is common in the volcanic-type feldspars of the xenoliths, the plutonic-type feldspars do not represent end stages of such transformations. The observations indicate no direct relation between the two groups of feldspars. The microcline and the albite (other than the core albite) were probably formed by recrystallization of newly crystallized volcanic-type feldspar and not primarily by structural inversion from a high-temperature form.

Transfer of Material between Xenoliths and Diabase

Whereas the granitic central zone is similar in composition to the parent rocks, the marginal zone is characterized by large amounts of hornblende and calcic pla-

gioclase. This and the change in calcium content of the plagioclase (see fig. 10) indicate a considerable transfer of material from the diabase to the marginal zone. The simultaneous disappearance of hornblende and andesine at the contact with the central zone is thought to represent the outer limit of diffusion of calcium, magnesium, and iron from the diabase.

The contact between marginal zone and diabase is sharp, and is marked by the much coarser grain of the diabase. These features suggest that no direct mixing of

TABLE 3

RELATIVE AMOUNTS OF RELICT QUARTZ AND PARENT QUARTZ

	Thin section no.	Quartz area (sq. units)	Total area (sq. units)	Quartz (per cent)
	92	167	687	24
Xenolith 1	93	160	420	38
(Relict quartz)	94	116	488	24
	95	268	890	30
				Av. 30
	1	66	564	12
Gneiss	2	50	765	7
(Parent quartz)	4	5	710	1
	38	75	702	11
				Av. 8
	43	92	604	15
Granite	45	135	540	25
(Parent quartz)	145	158	524	19
				Av. 20

granitic and diabasic magma took place. It is possible that the diabase was mostly solid before the inclusions were affected. This could also explain the dikelike shape of xenolith 2 (900 feet long by 15 feet wide), because partially liquid material may have been injected into partially crystallized diabase.

The "diabase" surrounding the inclusions is different from the normal diabase of the area in that it contains no pyroxene, but consists of green hornblende (50 per cent), calcic andesine (30 per cent), and quartz and graphic intergrowth (20 per cent). Since hornblende fills in between plagioclase laths much as does pyroxene in the normal diabase, the rock is referred to as a diabase. Addition of material from the marginal zone into the modified diabase is probable because of the increase in quartz and micropegmatite (1 per cent in the normal diabase to 20 per cent in the modified diabase). Also, addition of granitic material would allow crystallization to proceed to lower temperatures with appearance of minerals lower in the reaction series, such as hornblende.

Filterpressing

The relative amounts of relict quartz (xenolith 1) and the quartz present in the gneiss and granite are shown in table 3. The measurements suggest a packing together of the relict grains. If these measurements are representative, they mean that approximately 33 per cent of the material has been lost during modification of the xenolith. This calculated volume loss would be increased if the corrosion of the quartz were considered.

Narrow white dikelets occur locally in the diabase adjacent to the xenolith. The dikelets consist mainly of albite and quartz in granophyric intergrowth. The albite is An_3 with 2V 84° positive, and is twinned chiefly on the albite and pericline laws. Measurements of nine quartz-albite ratios in the granophyre suggest a tendency toward a ratio of 32 per cent quartz to 68 per cent feldspar. This is close to that determined from the nepheline-kaliophilite-silica phase diagram, which is about 34 per cent quartz to 66 per cent albite.

A survey of the literature shows that acid dikelets are often associated with strongly altered siliceous xenoliths in diabase. Walker and Poldervaart (1949) mention the common association of acid dikelets with xenoliths in Karoo dolerites. Mountain (1936) was able to show probable squeezing out of a liquid fraction leaving a quartz-enriched residue. In the present study the dikelets and the probable volume loss can be explained by a squeezing out of part of the liquid fraction produced by melting.

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LITERATURE CITED

Bowen, N. L.
1922. The behavior of inclusions in igneous magmas. Jour. Geol., 30: 513–570.

Chao, S. H., and W. H. Taylor
1940. The lamellar structure of potash-soda feldspars. Proc. Roy. Soc. London, A, 174: 57–72.

Emulus, C. H., and J. V. Smith
1959. The alkali feldspars. VI. Sanidine and orthoclase perthites from the Slieve Gullion area, Northern Ireland. Am. Mineral., 44: 1187–1209.

Fairbairn, H. W., and T. Podolsky
1951. Precision and accuracy of optic angle determination with the universal stage. Am. Mineral., 36: 823–832.

Folk, Robert L.
1955. Note on the significance of "turbid" feldspars. Am. Mineral., 40: 356–357.

Frankel, J. J.
1950. A note on the vitrification of Karoo sediment by dolerite intrusions. Trans. Roy. Soc. S. Africa, 32: 287–293.

Hamilton, Warren B.
1956. Precambrian rocks of Wichita and Arbuckle mountains, Oklahoma. Geol. Soc. Am. Bull. 67: 1319–1330.
1959. Chemistry of granophyres from Wichita lopolith, Oklahoma. Geol. Soc. Am. Bull. 70: 1119–1126.

Hawkes, L.
1929. On a partially fused quartz-feldspar rock and on glomerogranular structure. Mineral. Mag., 22:163–173.

Hewlett, C. G.
1959. Optical properties of potassic feldspars. Geol. Soc. Am. Bull., 70: 511–538.

Hotz, Preston E.
1953. Petrology of granophyre in diabase near Dillsburg, Pennsylvania. Geol. Soc. Am. Bull. 64: 675–704.

Ito, T., and R. Sadanaga
1952. The lamellar structure of certain microcline and anorthoclase. Acta Cryst., part 4, 5: 441–449.

Jones, W. A.
1930. A study of certain xenoliths occurring in gabbro at Sudbury, Ontario. Toronto Univ. Studies Geol. Ser. no. 29, pp. 61–73.

Knopf, A.
1938. Partial fusion of granodiorite by intrusive basalt, Owens Valley, Calif. Am. Jour. Sci., 36: 373–376.

Köhler, Alexander
1948. Erscheinungen an Feldspaten in ihrer Bedeutung für die Klärung der Gesteinsgenesis. Min. petr. Mitt., Band I, 51–67.
1949. Recent results of investigations on the feldspars. Jour. Geol., 57: 592–599.

Larsen, E. S., and George Switzer
1939. An obsidian-like rock formed from the melting of a granodiorite. Am. Jour. Sci., 237: 562–568.

Laves, Fritz
1952. Phase relations of the alkali feldspars, I and II. Jour. Geol., 60: 436–451, 549–575.

Leighton, M. W.
1954. Petrogenesis of a gabbro-granophyre complex in northern Wisconsin. Geol. Soc. Am. Bull. 65: 401–442.

Mountain, Edgar D.
1936. Syntectic phenomena in Karoo dolerite at Coedmore quarries, Durban. Trans. Geol. Soc. S. Africa, 38: 93–112.
1944. Further examples of syntexis by Karoo dolerite. Trans. Geol. Soc. S. Africa, 47: 107–122.

Nikitin, W.
1936. Die Fedorow-Methode. Borntraeger, Berlin.

Oftedahl, Chr.
1948. Studies on igneous rock complex of the Oslo region. IX. The feldspars. Norske vidensk.—akad. Oslo Skr. I Mat.-naturv. Kl., no. 3.

Osten, J. F.
1953. Identificatie van natuurlijke alkaliveldspaten met behulp van röntgen-poederdiagrammen. Leidse Geol., Med. dl., 17: 1–69.

Poldervaart, Arie
1952. Karoo dolerites and basalts in the eastern part of the Bechuanaland Protectorate. Trans. Geol. Soc. S. Africa, 55: 125–132.

Preuss, Ekkehard
1950. Der Meteorit von Oldenburg (Abstract). Fortschr. Mineral., 28: 63.
1951. Hochtemperatur-Plagioklas im Meteorit von Oldenburg, Heidelberg. Beitr. Min. Petr., 2: 538–546.

Reynolds, Doris L.
1936. Demonstration in petrogenesis from Kiloran Bay Colonsay. Mineral. Mag., 24: 367–407.

Schairer, J. F., and N. L. Bowen
1935. Preliminary report on equilibrium relations between feldspathoids, alkali feldspar, and silica. Trans. Am. Geophys. Union, part 1, pp. 325–328.

Smith, J. R.
1958. The optical properties of heated plagioclases. Am. Mineral., 43: 1179–1194.

Smith, J. R., and H. S. Yoder
1956. Variations in X-ray powder diffraction patterns of plagioclase feldspars. Am. Mineral., 41: 632–647.

Strauss, C. A.
1947. The petrology of a small dolerite and granophyre complex in the New Belgium block, Potgietersrust district. Trans. Geol. Soc. S. Africa, 50: 73–104.

Tröger, W. E.
1952. Tabellen zur optischen Bestimmung der gesteinbildenden Minerale. E. Schweizerbart, Stuttgart.

Turner, F. J.
1947. Determination of plagioclase with the four-axis universal stage. Am. Mineral., 32: 389–410.

Tuttle, O. F.
1952. Optical studies on alkali feldspars. Am. Jour. Sci., Bowen volume, pp. 553–567.

Tuttle, O. F., and N. L. Bowen
1950. High-temperature albite and contiguous feldspars. Jour. Geol., 58: 572–583.
1953. Beginning of melting of some natural granites. Carnegie Inst. Wash. Yearbook no. 52, p. 62.

Tuttle, O. F., and J. L. England
1953. Stability relations of the amphiboles. Carnegie Inst. Wash. Yearbook no. 52, p. 62.

Tuttle, O. F., and M. L. Keith
1954. The granite problem: evidence from the quartz and feldspars of a Tertiary granite. Geol. Mag., 91: 61–72.

Van der Kaaden, G.
1951. Optical studies on natural plagioclase feldspars with high- and low-temperature optics. Pub. van het Min. Geol. Inst. Ryks, Universiteit, Utrecht.

Wager, L. R., D. S. Weedon, and E. A. Vincent
1953. A granophyre from Coire Uaigneich, Isle of Skye, containing quartz paramorphs after tridymite. Mineral. Mag., 30: 263–275.

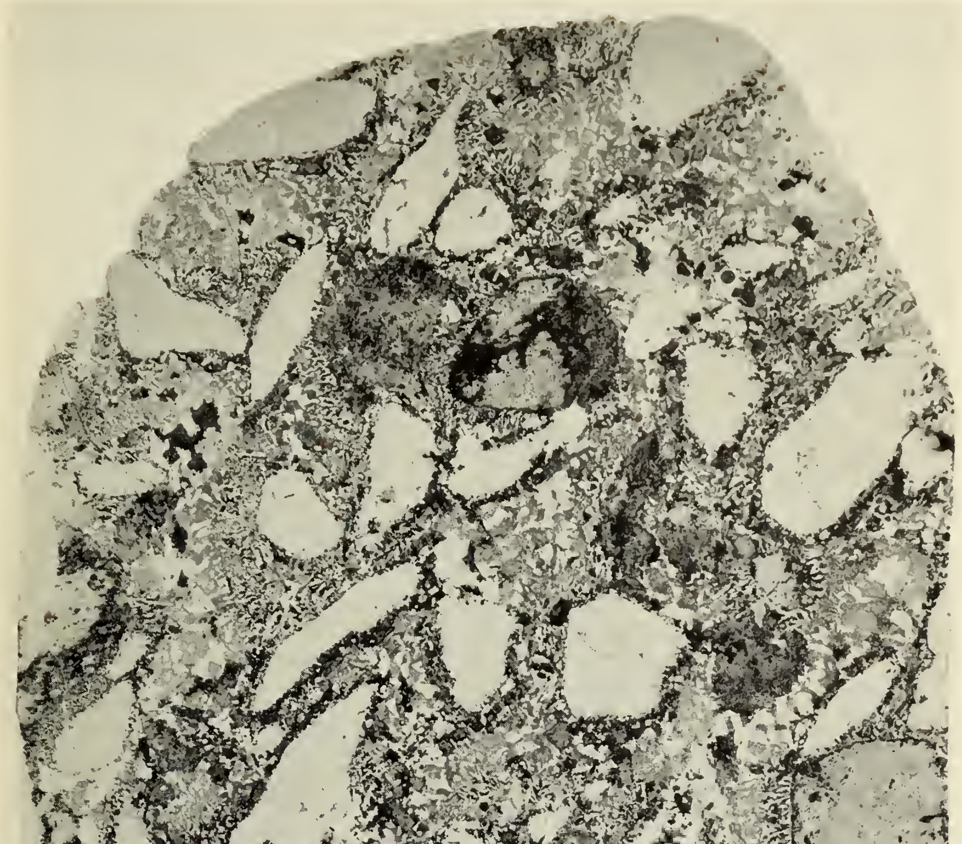
Walker, Frederick, and Arie Poldervaart
1949. Karoo dolerites of the Union of South Africa. Geol. Soc. Am. Bull. 60: 591–706.

White, J. F.
1955. Granitic xenoliths in diabase and associated high- and low-temperature feldspars (Abstract). Geol. Soc. Am. Bull. 66: 1669.

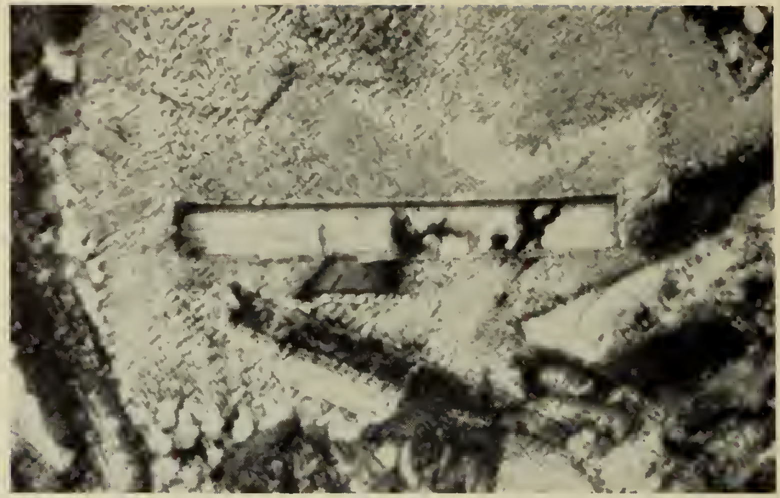
Wilson, Allan F.
1950. Some unusual alkali feldspars in the Central Australian charnockitic rocks. Mineral. Mag., 210: 215–224.

Wilson, A. F.
1952. Metamorphism of granite rocks by olivine dolerite in Central Australia. Geol. Mag., 89: 73–86.

PLATES

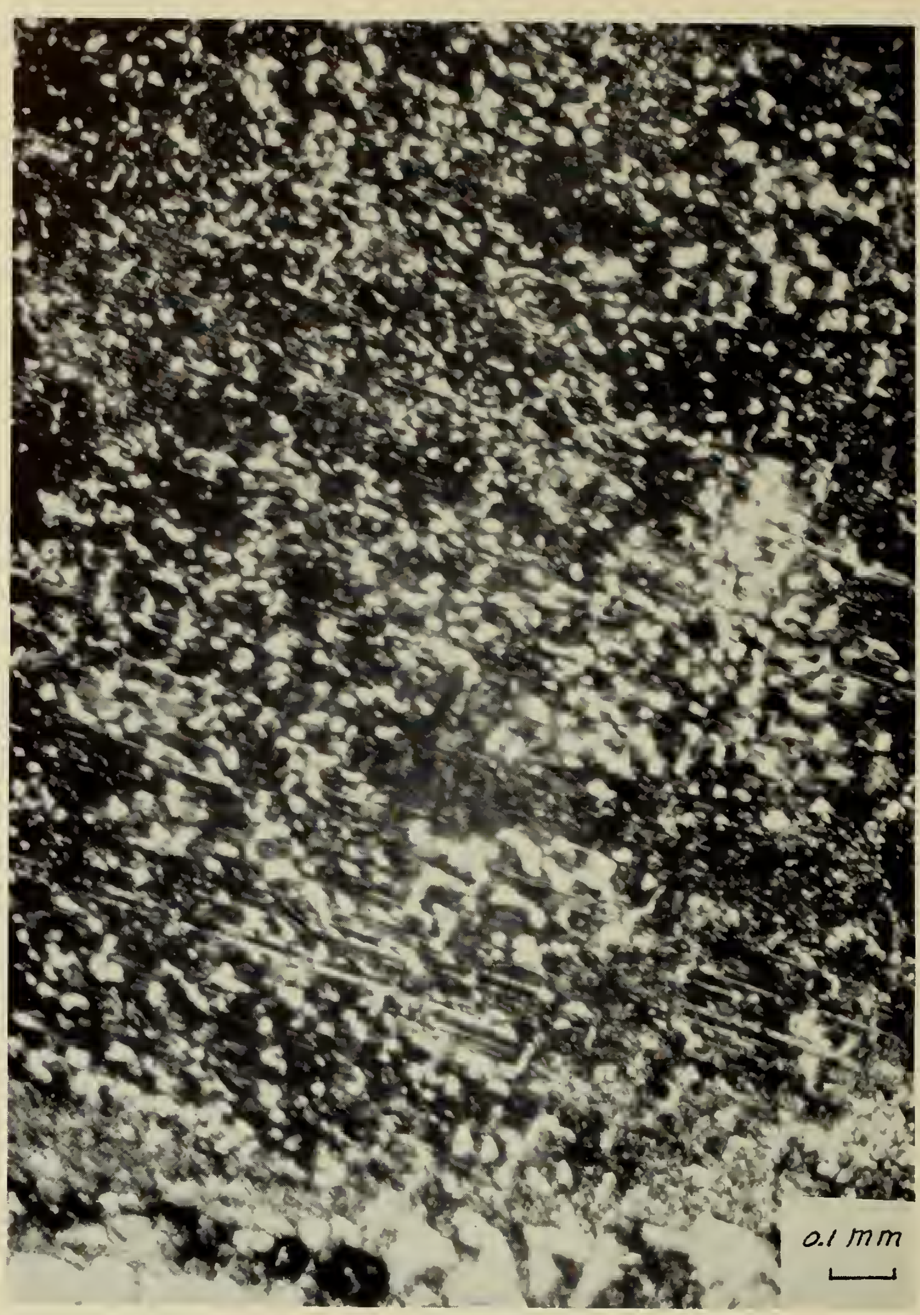


A typical specimen from xenolith 1. Large, clear, polycrystalline quartz grains, and large, rounded, murky feldspars in a fine-grained matrix of granophyric intergrowths. (Ordinary light.)



Core plagioclase (high-temperature). The core feldspar is located as a core to granophyric intergrowths of potassium feldspar and quartz. Length of the central feldspar is 0.4 mm. Surrounding granophyric intergrowth is especially fine-grained. From the margin zone of the xenoliths. (Under crossed nicols.)

The "mottled plagioclase" (approximately outlined in black) is a patchwork of subgrains of slightly different orientations. The speckled appearance is due to tiny blebs of quartz. Relict quartz body on left. (Under crossed nicols.)



Quartz intergrowth in mottled plagioclase. Quartz blebs are about 0.02 mm. in diameter. (Under crossed nicols.)